Aviation-class Synergistically Cooled Electric-motors with iNtegrated Drives (ASCEND)

Reaching Cruise Altitude?

Dr. Peter de Bock

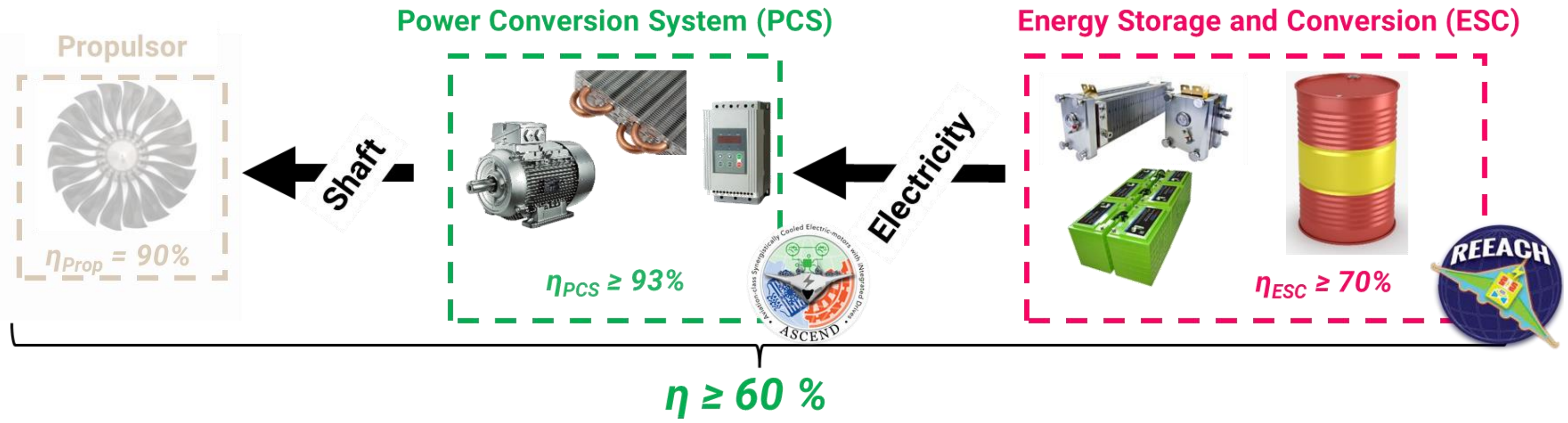
Acknowledgements:
- Dr. Rakesh Radhakrishnan
- Dr. David Tew
- Dr. Grigorii Soloveichik

- Dr. Michael Ohadi

ASCEND

- You are in the company of teams that are designing the **most compact** motors, power electronics and thermal management system **the world has ever seen** and leverage these for a decarbonized aviation future

- Motor+PE+TMS system
- Main Targets:
  - 12 kW/kg
  - >93% Efficiency



- Enable more efficient aviation propulsion system (with REEACH ESPG)
- Enable new concepts: Distributed Electric Propulsion(DEP), Boundary Layer Ingestion(BLI), Hybrid architectures, etc.

ASCEND – Program Overview

ASCEND

Aviation-class Synergistically Cooled Electric-motors with iNtegrated Drives

Mission

Development of innovative lightweight and ultra-efficient electric motors, drives, and associated thermal management systems (collectively referred to as the all-electric powertrain) that will help enable net-zero carbon emissions in single-aisle, 150-200 passenger commercial aircraft.

Program Directors	Dr. Peter de Bock / Dr. David Tew (Fmr. Dr. Michael Ohadi)
Year	2020
Projects	10
Funding Amount	$35 million

Goals

- Sets a benchmark of the fully integrated all-electric powertrain system at a power density of ≥ 12 kW/kg with an efficiency at ≥ 93%.
- Conceptual designs and computer simulations of the motor, its drive, and their integration, as well as subsystem/component level demonstrations for the proposed key enabling technologies to support the performance projections. (Phase 1)
- Development, fabrication, and testing of an integrated sub-scale all- electric powertrain (≥ 250 kW), including its thermal management system. (Phase 2)

Power Conversion System (PCS)

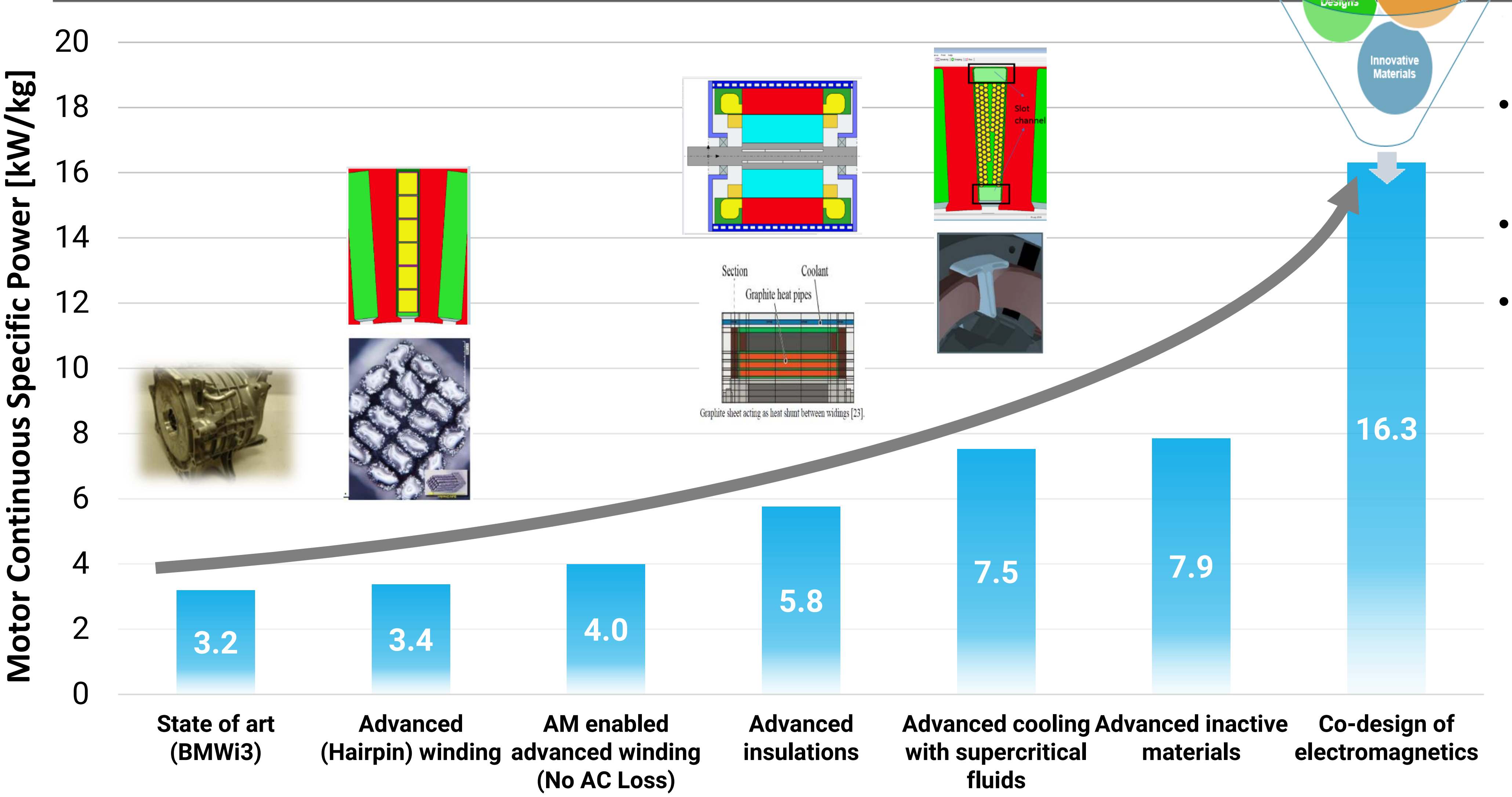
Status 6/2022: 10 teams @ 1year + 2 bonus teams

ARPA-E Summit 2022 Q2 2022
Annual meeting Q2 2022
→ Start focus on phase 2 prep

Phase 1 completion ~ Q4 2022

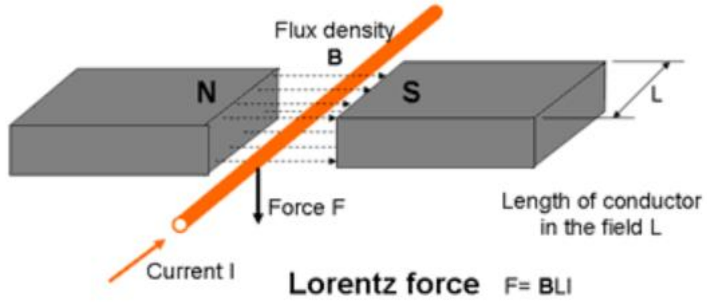
Transition phase 2 – 2023-2024
- Testing of motor + power electronics + TMS

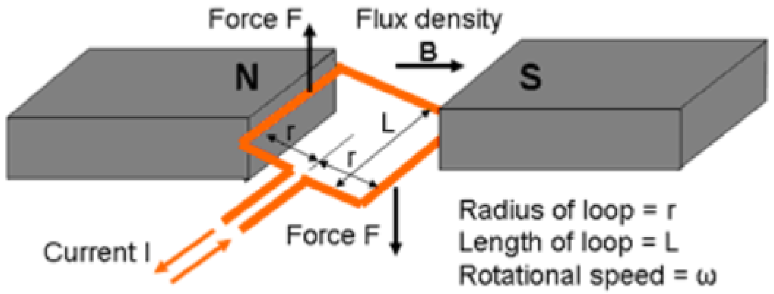
Variety of paths



- > 16 kW/kg can be achieved
- Efficiency of 95.4%
- **Further optimization is possible**!

Electric Motors Basics





Motor Torque = 2Fr = 2 BLIr (2 conductors)

Generator EMF = 2 BLrω

Apparent Power output of an electrical motor/generator:

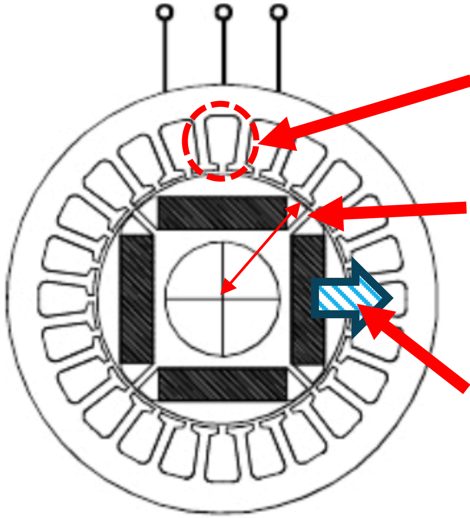
$$S = B_r^0 K_s \pi r_0^2 L_a \frac{\omega}{p}$$

Magnetic Loading (air gap flux density)
IM: 0.8T
PM: 0.9T
SC: >1.5T

Electrical Loading $= K_f K_w A$ → **Slot Current Density**

Active rotor volume

Rotation speed

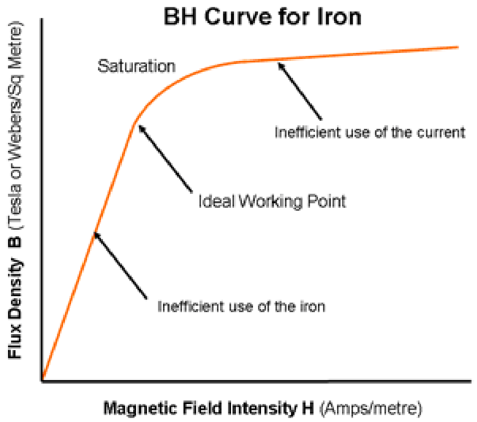


<u>For AC motors</u>, the rotational speed is proportional to the frequency of the applied voltage

<u>In DC motors</u> the rotation speed is proportional to the applied voltage

$$S \propto A \times \omega$$

The torque produced is proportional to the electrical loading until magnetization saturation is reached



From: https://www.mpoweruk.com/machines.htm Source: Miller, TJE, Switched reluctance motors and their controls, Magna Physics Pub, 1997

How do we get >12kW/kg Electric motors?

Specific Power

Current density

Fixed

$$\frac{P}{M_{total}} = \frac{\pi}{\sqrt{2}} \cdot k_{w1} \cdot k_f \cdot h_s \cdot \tau_{w/p} \cdot \bar{B} \cdot J \cdot \omega \cdot \frac{1}{\rho_{avg} \cdot \widehat{M}_{rat}}$$

Magnetic Loading

Density

Active Mass ratio

Maximum Temp. of conductors

$$J_{\text{therm}} = \sqrt{\frac{(\Theta - \Theta_{amb})}{\theta_{therm,total}} \cdot \frac{1}{m \cdot A_s \cdot \rho_{el}(\Theta) \cdot L_w}}$$

Thermal Resistance to ambient

Conductor electrical resistance

1. Increase Current Density (J)

Approaches:

- Reduce Thermal Resistance ($\theta_{therm,total}$)
- Increase Max. Temp(Θ)-insulation

Pros:

- Highest potential

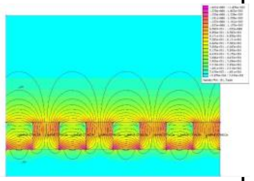
Cons:

- Impacts efficiency

2. Increase Magnetic Loading ($\bar{B}$)

Approaches:

- Hallbach
- Induction



Pros:

- Increased performance without efficiency penalty

Cons:

- PM systems limited by temperature

3. Decrease Avg Density(ρ_{avg}) & active tot weight ratio($\widehat{M}_{rat}$)

Approaches:

- Composite mat's
- Hairpin windings
- Co-design parts (i.e. structural + fluid manifold)

Pros:

- "Free" weight red.

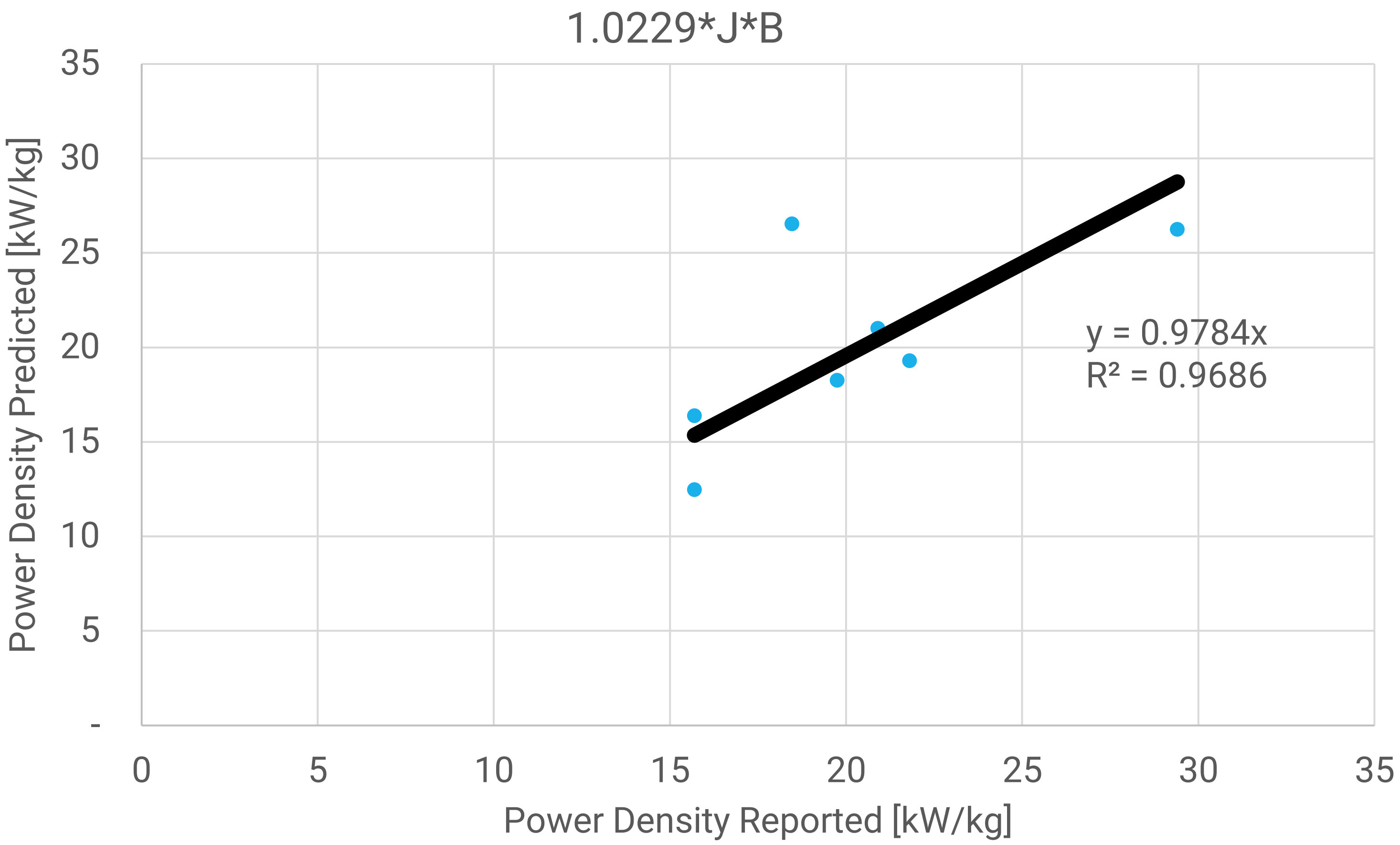
Cons:

- Can limit Temp.

$\bar{B}$	Radial flux density, T
D	Rotor diameter, m
J	Slot current density, A/m^2
h_s	Slot height, m
k_f	Slot fill factor, %
k_{w1}	Fundamental winding factor
L	Machine core length, m
M_{total}	Machine total mass, kg
$\widehat{M}_{rat}$	Active to total mass ratio
P	Power, W
θ_{therm}	Thermal resistance, K/W
T	Torque, N-m
Θ	Temperature of the conductor, K
Θ_{amb}	Temperature of ambient, K
$\tau_{w/p}$	Slot width to pitch ratio, %
ω	Rotational speed, rad/s
ρ	Density, kg/m^3
ρ_{el}	Electrical resistivity, Ω-m

J*B product correlates w/ Power Density

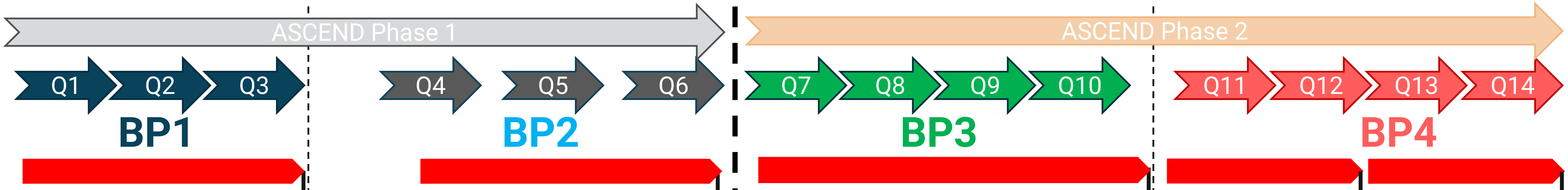
- Current density linearly improves specific power



ASCEND Technology Chart

CHANGING WHAT'S POSSIBLE

Typical Project Timeline, Technical Milestones (14 Quarters)



Detailed design

Key Components de-risking and testing

Sub-systems build ….

… & test

Final deliverable (250 kW) testing in laboratory

Q3 Milestone:
Detailed multi-level modeling of thermal, electromagnetic and structural performance prediction and validation of system and sub-system metrics.

Q6 Milestone:
Models are calibrated through scaled experiments of

Key deliverables:
- **Demonstrate Slot Current density with proposed TMS**

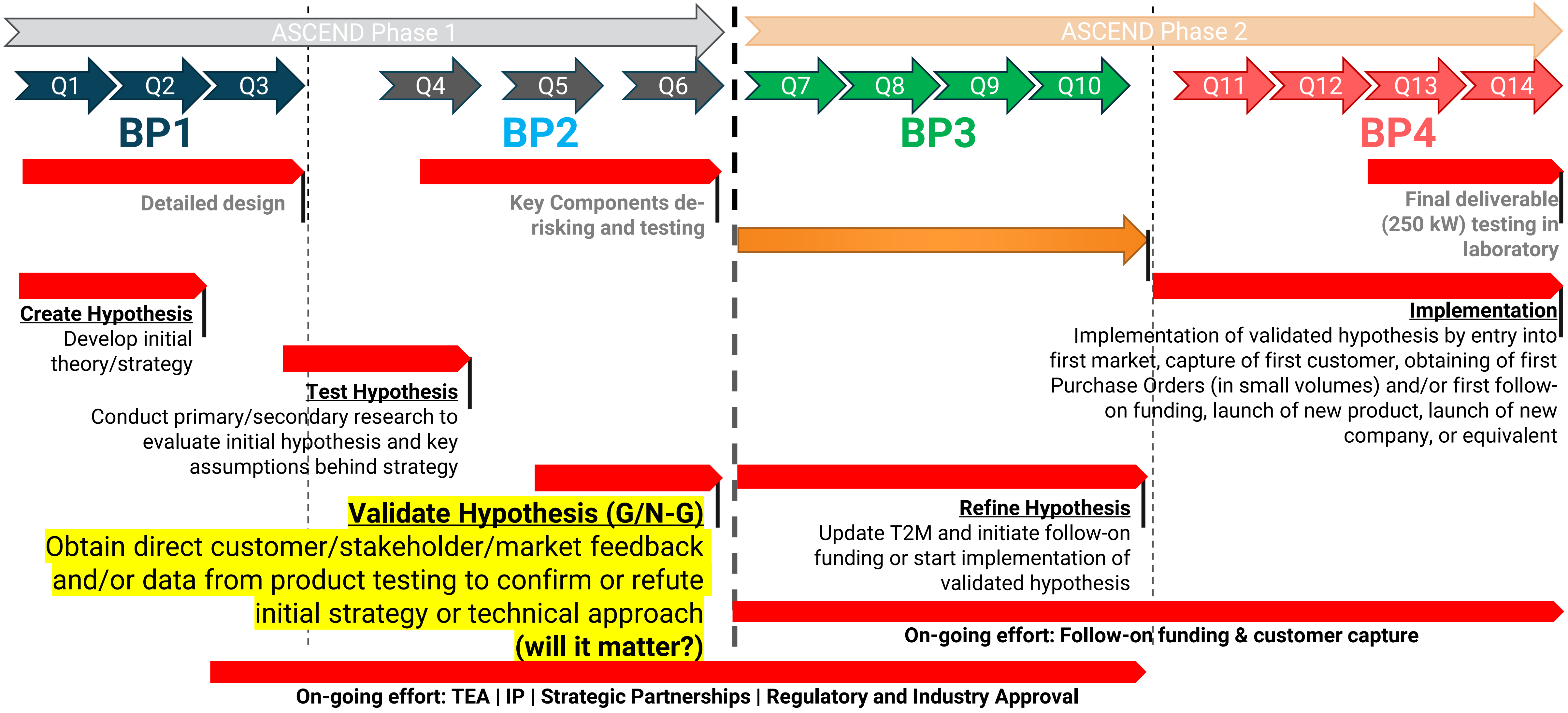
(will it work)?)

Q10 Milestone:
The components for the prototype have been acquired and the motor, inverter, and TMS subsystems have been successfully assembled.

Q12 Milestone:
Subsystem test completed. Start system integration.

Q14 Milestone:
Complete system integration and its testing under the load profile as described in ASCEND FOA Figure 5.

Typical Project Timeline, T2M Milestones (14 Quarters)



Wrap-up

- Great work in phase 1; exciting to see the concept technologies mature
- Community of performers with variety of technology approaches; collaborate when possible!
- Integration and co-design of power electronics, motors + thermal management system challenge & opportunity

- Phase 1; demonstrate your de-risked concept
  - Current density A/mm^2 w/ proposed TMS at design temperature rise
  - T2M: Develop strategy and get feedback on technologies specific to your design, fine tune if needed → plan for it to matter if succesful

- Phase 2; build and test the world's most power dense motors, decarbonize aviation
  - Build and demonstrate ASCEND prototypes
  - T2M: Make sure that it matters!

Please put me in a position where all teams show incredible Technical merit and incredible Tech2market potential

If it works…

will it matter?

https://arpa-e.energy.gov